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OurOwnsKIN

The Development of 3D-Printed Footwear Inspired by Human Skin

Manolis Papastavrou, Liz Ciokajlo, and Rhian Solomon

Introduction

OurOwnsKIN[1] is a research project exploring the interplay between man, material, and machine to create innovative footwear design constructions inspired by human skin. The aim is to harness the capabilities of 3D printing in preparation for future biotechnologies.

Could a deeper understanding of how our skin behaves as a material inform the design of 3D-printed shoes?

Today's digital technologies and tomorrow's biomaterials present vast opportunities but also challenges to the way footwear is designed, urging designers to define systems of making that emerge directly from radical changes in material and process.

Manufacturing is moving toward new territories whereby 3D printing is allowing us to construct exceptionally fine and intricate features with high accuracy "enabling design to take place concurrently at scales ranging from the micrometre to the metre" (Beckett and Babu 2014: 113). Properties of materials are effectively becoming defined through the design of their inherent microstructure. In parallel, biotechnology is also providing sustainable materials that are cultured in a laboratory, posing very real alternatives to polymer synthetics and leathers in the fashion industry.

Figure 10.1 OurOwnsKIN 3D-printed shoe inspired by human foot skin (2017). Film by Craig Gambell and George Ellsworth; OurOwnsKIN directed by Liz Ciokajlo and Rhian Solomon.

While inspiration for future footwear will undoubtedly be informed by new materials and technologies, in order to make designs more relevant to our anatomy and more relatable to humans, the OurOwnsKIN project argues that influence must also come from ourselves, the materiality of our own bodies (Figure 10.1) … Our skin.

By studying the interface that connects us most intimately with our world, can we perhaps propose new design approaches that inform materials, machine, and resultant products?

Man–matter–machine

Our skin has arguably been evolving for the last 300,000 years (Hublin et al. 2017). Paleoanthropologist Erik Trinkaus (based on his studies into the evolution of human toe bones) proposes that humans have been wearing footwear for roughly 40,000 years (Trinkaus 2005); appropriating the skin of another animal to produce footwear for around 5,500 years, as evidenced by the oldest found leather shoe (Pinhasi et al. 2010).

Leather (and a detailed knowledge of its structure) has had a formidable influence on the way that we manipulate sheet materials in shoe constructions, evolving systems of footwear production as we know them today.

The pattern cutting of leather for shoes, for example, is a sophisticated process that exploits the properties of skin in its application. Cobblers will map lines of minimal and maximal stretch on leather hides to inform how they are cut and reassembled to make shoes; poetic designs such as the welted brogue[2] comprise of multiple sections of the hide, arranged in a way that reflects the different performative parts of the shoe.

When a footwear designer develops a design, he or she is working within a well-established system of making that considers numerous parameters associated with the shape of the shoe; the last,[3] fit points on the foot,[4] pattern cutting, the selection of material, employment of machines, and, finally, the entire assembly process.

Each established system determines an archetypal design; the brogue, stiletto, and wellington boot have all been informed by the leading available materials and processes of their time, in turn creating an entirely new category of footwear.

A detailed knowledge of leather and its intrinsic material properties has driven hand-production processes to create these designs. It is the archetypal designs themselves, however, that have shaped the automation of footwear production (and resultant machinery) during the industrial age.

Twentieth-century machines vs twenty-first-century technologies

The Industrial Revolution was driven by the need to mechanize industry, in order to automate repetitive hand-making processes (Shawcross 2014). This resulted in footwear design constructions made by hand significantly influencing the design of the machines used in their production.

Manufacturing techniques became responsible for driving the performance specifications and aesthetics of a shoe, locking designers into regimented ways of making as too much time, skill, and finance became invested by industry.

Despite the introduction of "new" materials, such as polymers during the Plastics Age of the mid-twentieth century, standardized footwear production techniques prevailed. As the century progressed, digital machines began to be introduced, making it more efficient for goods to be produced within the factory and for designers to instruct from their desk.

The development of computer-aided design (CAD) software tools, such as Adobe[5] and SolidWorks[6] suites for 2D and 3D technical drawings also gave designers the freedom to send design instructions to factories across the world, without ever having to be there in person. Efficiency became the catalyst for producing faster machines, motivating designers to adopt rapid digital design methods as a result.

Form driven by machine, material . . . or body?

Materials anthropologist Susanne Küchler describes how the manufacturing and commoditization of products in the Industrial Revolution occurred in parallel to the commoditization of the materials supplied to such factories (Drazin and Küchler 2015). A system to manufacture materials was effectively shaped by a system that manufactured machines.

Just as hand-made shoe processes informed the design of machines that automated hand tasks, there needed to be direction as to what form materials would take in order to be supplied to factories. An interplay between machine and material factors started to define the parameters from which a designer made construction design choices.

Materials were (and still are) largely supplied in the form of sheets, ready to be cut and constructed, molded polymers also tending to have one consistent property, a given stiffness and density. Late twentieth-century footwear designers would work with the properties inherent in the extended range of materials on offer, to command shoe functions, joining a variety of materials together when a change of performance was required. The dominant construction technique that persisted (even to today) was the connection of an upper,[7] or top part of the shoe, to its outsole.[8]

In the evolution of footwear manufacturing, machines and matter became the defining industry systems in the hierarchy of how things were made. Form and finer details of construction were the only possible variables for altering the property of a given material, in turn defining the overall aesthetic of a design.

The promise of Additive Manufacturing

Since the dawn of the twenty-first century, new manufacturing technologies and design tools have been introduced, namely Additive Manufacturing[9] (AM) and advanced computational design, allowing the designer to specify the behavior of a material in ways never achieved before.

Opportunities afforded by this technology have led to a rapid transformation in manufacturing, as products and components are redesigned to capitalize on its unique advantages, which include the light weighting of parts, enhanced customization, and the production of highly complex forms.

Global performance sportswear companies currently adopting AM techniques in the production of components for commercial footwear include Adidas for 3D-printing parametrically designed midsoles (Futurecraft); Nike for developing a 3D-printed upper (Flyprint); and New Balance, in collaboration with Nervous System, who have used pressure data taken from runners to construct 3D-printed midsoles to a shoe (data-driven midsoles).

The footwear industry is yet to embrace the full capabilities of 3D printing, however, as it continues to apply conventional multipart assembly systems, overlooking the opportunity to specify the material density and performance features across a shoe comprising a single part—the influence of the laced brogue construction prevails. It is also not uncommon in footwear innovation departments for managers to ask for laces to be added to radical designs, in order to make them more "shoe-like."

Computer-aided design

To fully capitalize on the design freedom available through AM advanced digital design tools are required. Conventional approaches to CAD are limited in terms of the complexity of forms and features that they can produce. Computational or parametric design[10] remains one of the only methods capable of generating highly complex forms in 3D space.

In Grasshopper[11] for Rhinoceros[12] the designer can define the form of an object by linking different elements of a digital model together using parametric relationships. When applied to 3D printing, this allows for the precise control of different processing and material parameters during the fabrication of a part, as the object is built layer by layer.

AM and its associated CAD tools (in addition to opportunities provided by biotechnologies) are undoubtedly revolutionizing the way that we design and fabricate products in the twenty-first century—marking a shift from a "structure-driven" to a "material-driven" approach to design (Oxman 2010).

Küchler suggests that the real innovation of 3D printing is not the objects that we produce using this technology or how we revolutionize manufacturing, it is the way that 3D printing changes a designer's mindset on how objects can be constructed; "how the mind will inhabit this material technology that calls for and creates structures of internally held, manifold relations" (Küchler 2014: abstract).

Archetypal designs in 3D-printed footwear

Deyan Sudjic, design writer and Director of the Design Museum in London, has described archetypal designs as designs so unique that they define their own category (Sudjic 2009). As this chapter has demonstrated, archetypal designs of the past, such as the brogue, have been greatly informed by the properties of materials available to designers (namely leather), and by the techniques and technologies developed for their manipulation and mass manufacture.

Currently, however, there exists no established system for evolving 3D-printed shoes. Designers must therefore generate new reference points to inform future footwear constructions when using this technology.

Can human skin act as inspiration for archetypal 3D-printed shoes—whereby design is not determined by a machine, or conventional forms of matter, but by an inherent understanding of our bodies?

The OurOwnsKIN project set out to disrupt current approaches to 3D-printed footwear by employing the knowledge of the anatomy of human skin to create 360° responsive shoes.

Collaborate

Rethinking the process of designing and manufacturing 3D-printed shoes is a highly complex problem that requires the employment of interdisciplinary teams. The OurOwnsKIN team consisted of a design researcher and visual artist (Rhian Solomon), a materials specialist with a background in chemical engineering and industrial design (Manolis Papastavrou), and a concept development footwear designer (Liz Ciokajlo)—each with a unique knowledge of the human body, materials, manufacturing, and form.

Rhian Solomon brought to the team insights into how skin behaves from the people who work with skin as a material—reconstructive plastic surgeons. This was drawn from previous innovation projects that she had facilitated across design and medical sectors—sKINship[13] (Ravetz, Kettle, and Felcey 2013; Solomon 2013) (Figure 10.2). Whilst disciplines have traditionally been divided and defined by the formation of practices associated with the body (Blackman 2008), Solomon considers "our body as the meeting place"; an opportunity to open dialogue between diverse communities. (Solomon 2018) (Figure 10.2).

Manolis Papastavrou offered specialist technical knowledge in AM, as well as methods for extracting principles from biological systems, translating them into design solutions. This was based on recent research in which he developed

Figure 10.2 Skin or Cloth? A film comparing plastic surgery and pattern-cutting techniques (2012) by Rhian Solomon.

novel AM techniques to create synthetic bone substitutes (Papastavrou 2016) (Figure 10.3).

Liz Ciokajlo provided an understanding of how footwear construction has evolved in relation to materials and fabrication processes, being interested in the changing role of the designer in specifying material properties that could inform future design archetypes.

Previous projects had included working with non-woven materials, as in the GreyFeltShoes (Figure 10.4, left) and biomaterials in projects such as the Mars Boot (Figure 10.5).

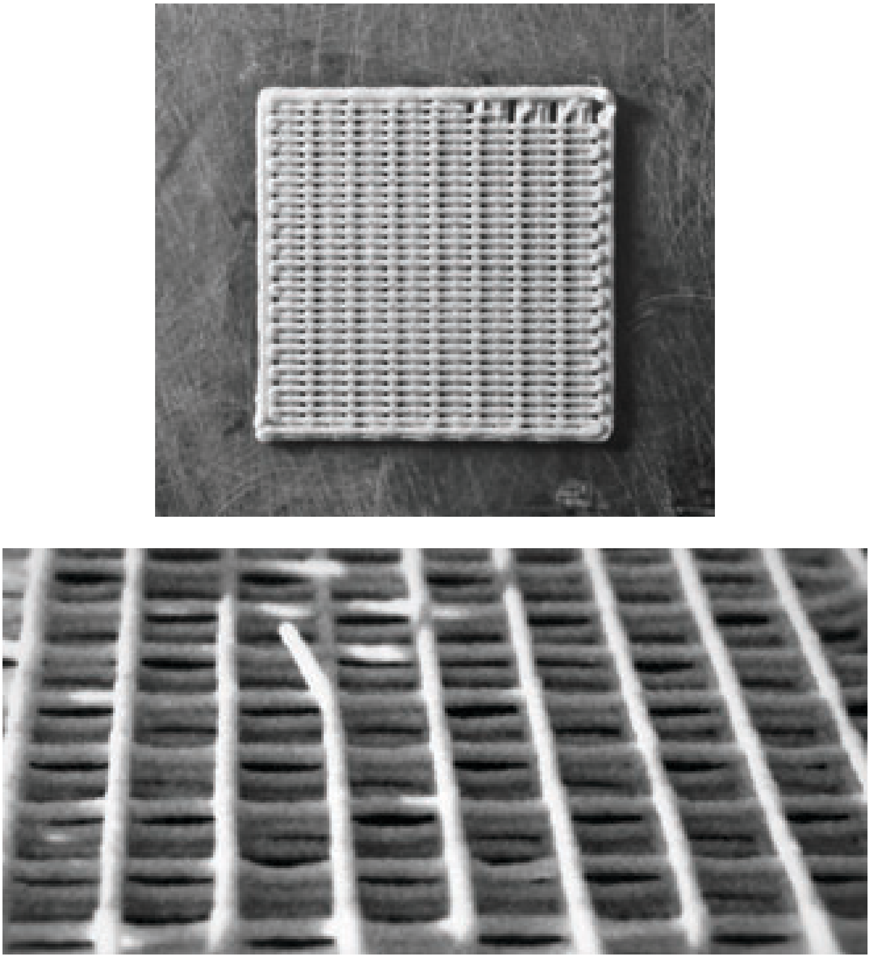

Figure 10.3 Bio-ceramic lattice structures fabricated using an extrusion based AM technique (2016) by Manolis Papastavrou.

Her collaboration on the BioCouture "Grown Shoe" (Figure 10.4, right) was also one of the catalysts for the OurOwnsKIN project as it questioned how our desire to recreate the familiar might impact on design innovation. The piece purposefully employed iconic brogue patterning in a bid to make bacterial cellulose more accepted and relatable as a leather alternative.

If we are working with radically new technologies and materials, what should inform resultant designs? Does a completely new production process require a completely new point of reference?

Figure 10.4 (left) GreyFeltShoes with additive binders, creating three levels of density over a continuous surface (2013) by Liz Ciokajlo. Photograph by Stephanie Potter Corwin; (right) the BioCouture "Grown Shoe" made from bacterial cellulose, Liz Ciokajlo (footwear designer) in collaboration with Suzanne Lee (art director) (2013). Photograph by Bill Waters.

Figure 10.5 Mars Boot—Mycelium variants and 3D-printed auxetic sole, Liz Ciokajlo in collaboration with Maurizio Montalti, Manolis Papastavrou, and Rhian Solomon (2017). Photograph by George Ellsworth.

Body matter—material properties of skin

Exploring skin as a source of inspiration, the team first needed to understand its behavior and the principles associated with its function.

Skin protects the underlying tissue structures of the foot by enveloping or wrapping around its complex contours; conforming to its ever-changing shape as it flexes and rotates (Langer 1978). It continuously remodels and adapts to the environmental conditions it is subjected to—a common strategy among tissues, including bone (Thompson and Bonner 1992).

Consisting primarily of two materials—collagen (dermis) and keratin (epidermis)—skin is arranged in a multitude of ways at different scales. Its mechanical properties and thickness transition gradually from elastic to rigid and from thick to thin across the human body in its entirety. Despite being localized, these properties do not appear as distinct zones but rather as gradients (Humbert et al. 2017).

Skin has a grain, just as cloth has a grain, which is dictated by how collagen fibers align themselves. In 1861, Austrian anatomist Karl Langer demonstrated this principle using a round-tipped instrument to make perforations on the skin of hundreds of cadavers. The skin's intrinsic tension would transform the wounds from round to elliptical, with their principal axis revealing each time the orientation of collagen fibers across the entire body (Humbert et al. 2017) (Figure 10.6).

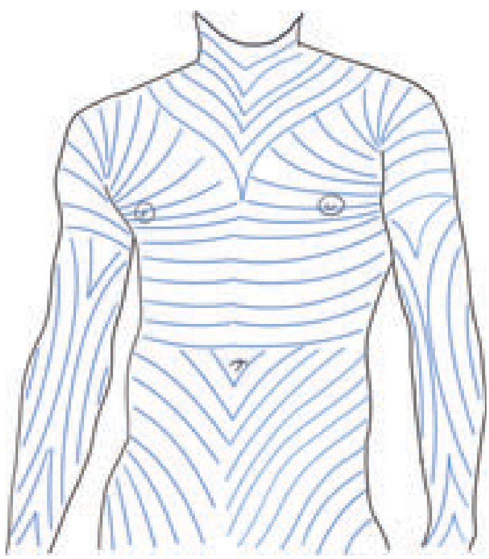

Figure 10.6 Illustration showing Langer's Lines mapped across the human body (2018) by Manolis Papastavrou.

Bioinspired design

Mimicking rather than copying (or growing) human skin was deemed the most viable route toward a functional footwear product for the OurOwnsKIN project, as shoe construction requires materials with reproducible properties that can be retained at conditions of high pressure or temperature.

Grown materials are not yet resilient enough for use in this particular context (Viney and Bell 2004). Typical problems such as the complexity and duration of their production also persist due to the high levels of investment that are required to convert traditional manufacturing into systems of biofabrication.

We are, however, on the cusp of a biomaterial revolution that is being driven by an evolving community of designers, scientists, and visionaries who are advancing sustainable biomaterials and production processes.

A future strand to the OurOwnsKIN project will seek to harness the capabilities of this technology, combining it with 3D printing; however, it was decided that the current project would take inspiration from the design principles of skin as a material, instead of replicating the biological process of its growth and regeneration.

Design development

The first developmental stage of the project was to establish a computational framework, inspired by human skin, that was both responsive and dynamic.

The mechanical behavior of skin has been described by Ridge and Wright using a simple orthogonal mesh positioned diagonally in relation to Langer's Lines (Ridge and Wright 1966) (Figure 10.7, top). The mesh is stretched more in one direction than the other, causing its cell units to deform into rhombi (diagrid). This could be visualized by a continuous braided structure, wrapped around the human body, that is not static, but constantly changes with body movement as it gets pulled in different directions.

Using Grasshopper for Rhino, the OurOwnsKIN team generated a diagrid lattice on a surface obtained from a foot scan (Figure 10.7, bottom right). Each member (or strut) of the lattice behaved like a spring under tension or compression—an approach which has the advantage of manipulating a "digital skin," by assigning different values of elasticity (stretching force) in each section of the foot, and making possible the complete customization of fit.

Figure 10.7 (top) Simplified model of the mechanical behavior of skin under tension proposed by Ridge and Wright, illustration by Manolis Papastavrou (2019); (bottom left) Directional grain of Langer's Lines as positioned on the human foot skin, illustration by Manolis Papastavrou (2019); (bottom right) OurOwnsKIN diagrid framework generated over scanned surface of the foot using Grasshopper for Rhino by Manolis Papastavrou (2017).

Auxetic lattices and footwear prototypes

In order to vary the stiffness in structures consisting of single materials, the team experimented with using lattices called auxetics. Auxetics are a family of lattices with a unique mechanical behavior; when stretched, they become thicker. Similarly, when compressed, they shrink and become stiffer.

The project employed two of the most popular types:

- the "bow tie" lattice—consisting of bow tie shaped cell units
- the "chiral" lattice—consisting of chiral shaped cell units

Each type of auxetic cell unit was inserted into the diagrid mesh framework in order to design and fabricate, what is called in the footwear industry a series of "socks."[14] This framework allowed for the variation of scale and the distortion of cell units, adapting to the contours of the foot in different areas while following the skin's tension lines.

Samples using these structures were initially 3D printed in a low-cost nylon 12 material, using selective laser sintering[15] (SLS). This was found, however, to be too rigid (Figure 10.8). The team decided to pursue using thermoplastic polyurethane (TPU) for further printouts, which offered an alternative material that was both durable and flexible.

These samples fully exploited the capabilities of 3D printing by rejecting a conventional upper and outsole footwear construction system. Printed in one

Figure 10.8 OurOwnsKIN 3D-printed "sock" using chiral auxetic pattern. Film by Craig Gambell and George Ellsworth (2017); OurOwnsKIN directed by Liz Ciokajlo and Rhian Solomon.

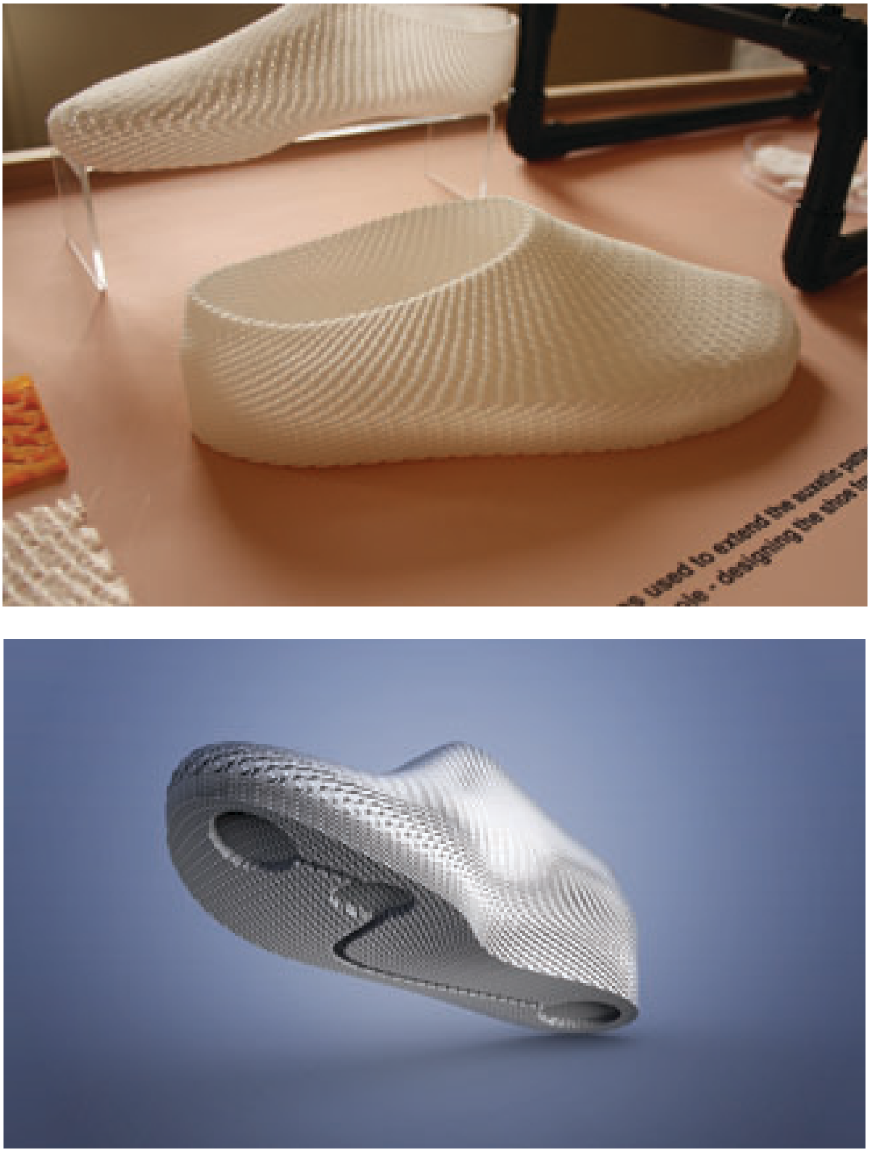

Figure 10.9 (top) OurOwnsKIN 3D-printed shoe featuring generated outsole (2016). Photograph by Manolis Papastavrou; (bottom) Evolving the aesthetic of the OurOwnsKIN 3D-printed shoe (2016). CAD file produced by Jason Taylor; OurOwnsKIN directed by Liz Ciokajlo and Rhian Solomon.

part, from a continuous mono material, they enveloped the foot in its entirety, creating a structure that was not only responsive to both movement and pressure but also integrated a closure system, requiring no need for traditional laces. The use of auxetic cells and personalized production processes (working from scans of the foot), also provided a bespoke fit and enhanced comfort for the wearer.

Subsequent stages of the project looked to generate an outsole to the shoe by extending the auxetic framework from its base, while at the same time maintaining a purity of form (Figure 10.9, top). The skills of additional CAD designers were also drawn upon to explore further variations of mesh.

Jason Taylor, of make X design,[16] coded the design structure onto a last, resulting in an evolved aesthetic for the shoe (Figure 10.9, bottom). The rationale for this exploration was to investigate manufacturing opportunities that might encompass the standardization of production.

Tom Mallinson, of Digits2Widgets,[17] developed a series of prototypes that added complexity to the structure by using 3D auxetic lattices, the aim being to enhance the performance of the shoe in areas under step impact.

Electrospinning

Each of the shoe samples required waterproofing or covering in some way. Reluctant to fill the structures using infill materials (which might have impacted on the stretch and responsiveness of the auxetic framework) the pieces were electrospun, creating a non-woven coating to the shoe. This process was also carefully selected so as to maintain the project's principle of rejecting conventional footwear manufacturing processes; moving away from sheet-formed material.

Electrospinning is a method that uses electrostatic forces to draw charged threads of polymers onto an oppositely charged surface. A thin coating of an highly elastic co-polymer PLA + polycaprolactone (PCL) formulation was applied to the shoe as it rotated on a lathe to create a fine non-woven scaffold (Figure 10.10). The thickness of the material can easily be tuned through altering the duration of this process.

Used frequently in medical applications in the production of wound-care products, implant coatings, and drug delivery systems, electrospun fibers hold incredible material properties as they support the growth of biological materials and can also be sustainable. The introduction of these fibers has opened opportunities to the OurOwnsKIN project to combine digital and biotechnological approaches to production. The next phase of the venture will aim to grow materials into the micro structures of electrospun, 3D-printed shoes.

Figure 10.10 Electrospun fibers applied to the OurOwnsKIN 3D-printed shoe (2016). Photograph by Manolis Papastavrou; OurOwnsKIN directed by Liz Ciokajlo and Rhian Solomon.

Future manufacturing opportunities

The OurOwnsKIN project has attracted interest from international research groups and major footwear companies through its bid to subvert current industry practices.

Benefits of methods such as this include shorter production timescales, by significantly reducing the number of processes, tools, and machines required; in turn lowering financial investment.

Parametric design also enables the industry to make changes more easily and cheaply during the early design phases of a shoe, allowing for mass customization and tailored fit. When coupled with AM this means that products can be produced for specific user groups, in small runs of production.

The OurOwnsKIN project in particular allows for the customization of fit to be distributed across different elements of a shoe (contour, material, and structure) resulting in a design that fits a wider population for mass production scenarios.

A final word . . .

OurOwnsKIN is a speculative project that positions the human body as the blueprint to instruct future design form and digital making processes. It is an approach that flies in the face of traditional sheet production techniques; one that is not driven by conventional materials, machines, or established design forms, but is driven by our own anatomical makeup.

As this chapter has identified, 3D printing (and biotechnologies) are today allowing us to subvert thousands of years of hand and machine-based construction knowledge—enabling a migration toward a future whereby form may be driven by algorithms, or choreographed by cell growth.

This raises questions, however, around the potential of these technologies to disrupt our emotional connections to the items that we choose to consume and wear. Whereby once humans appropriated the skin of another animal, now there is opportunity to wear our own skin, or "cloth" inspired by its materiality. What happens, therefore, when our relationship with commercial products is derived from the emotional connections that we hold with ourselves and our bodies? Will this enhance our intimacy with things—building resilience into associations between people and products. Or will this purely repulse us?

The OurOwnsKIN project additionally challenges our current relationship with the natural world from which we have become both separate and superior, following gross exploitation of the agricultural and industrial ages (Morton 2016). Perhaps a technique such as this, in which the materiality of the human body is reconsidered to produce commercial goods, can somehow integrate us back into nature, enhancing our empathy for the ecosystems in which we currently coexist?

If leather and its associated processes have been the driving force behind footwear manufacturing to date, can our own skin become the material that drives 3D-printed design form constructions of the future?

Acknowledgments

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Notes

1 OurOwnsKIN is both a research project and innovation design consultancy directed by Liz Ciokajlo and Rhian Solomon. See http://www.ourownskin.co.uk, http://www.lizciokajlo.co.uk, and http://www.rhiansolomon.co.uk.

2 The brogue is a style of low-heeled shoe or boot traditionally characterized by multiple-piece, sturdy leather uppers with decorative perforations and serration along visible edges.
3 A last is the hard form that represents the foot used in footwear construction. Depending on the manufacturing process to make the shoes, a last will be made from wood, aluminum, or, most commonly, plastic.
4 Fit points are key measurement points on a foot that are used to ensure the best fit and wearing of a shoe.
5 Adobe Suite is a suite of computer drawing software (including Illustrator and Photoshop) used by footwear designers to draw and specify designs.
6 SolidWorks is a CAD program commonly used by footwear designers to design the outer sole units of polymer shoes.
7 An upper is the part of the shoe that covers the top part of the foot from heel to toe and does not include the sole.
8 The outsole is the bottom most part of the shoe that comes into contact with the ground.
9 AM encompasses a great number of manufacturing techniques that share a common approach: the object is built layer by layer, allowing for the precise control of its internal architecture and composition (Campbell et al. 2012).
10 Parametric design is a process based on algorithmic thinking that enables the expression of parameters and rules. Together these define, encode, and clarify the relationship between design intent and design response.
11 Grasshopper is a visual programming language and environment that runs within the Rhinoceros CAD application.
12 Rhinoceros is a commercial 3D computer graphics and CAD application program developed by Robert McNeel & Associates.
13 sKINship is a collaborative network promoting cross-disciplinary interactions between visual arts and science-based practitioners—namely reconstructive plastic surgeons and designers who create and make for the body. See: http://www.skinship.co.uk.
14 A "sock" in the footwear industry is a thin piece of material that lies inside the shoe and surrounds the foot. A footwear "sock" is part of the shoe.
15 Selective laser sintering is an AM technique in which tiny particles of plastic, ceramic, or glass are fused together by heat from a high-power laser to form a solid, three-dimensional object.
16 make X design is a multidisciplinary consultancy designing digitally manufactured prostheses. See: http://www.makexdesign.com.
17 Digits2Widgets is a London-based consultancy specializing in 3D print, CAD, and scanning technologies. See: https://www.digits2widgets.com/.

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